

# Search for Lepton Flavor Violating $\tau^-$ Decays with a $K_S^0$ Meson

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## Abstract

We have searched for the  $\tau$  lepton flavor violating decays  $\tau^- \rightarrow \ell^- K_S^0$  ( $\ell = e$  or  $\mu$ ), using a data sample of  $281 \text{ fb}^{-1}$  collected with the Belle detector at the KEKB  $e^+e^-$  asymmetric-energy collider. No evidence for a signal was found in either of the decay modes, and we set the following upper limits for the branching fractions:  $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.6 \times 10^{-8}$  and  $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.9 \times 10^{-8}$  at the 90% confidence level. These results are improvements by factors of 16 and 19, respectively, compared with previously published limits from CLEO.

PACS numbers:

## INTRODUCTION

Lepton flavor violation (LFV) is allowed in many extensions of the Standard Model (SM), such as Supersymmetry (SUSY) and leptoquark models. Lepton flavor violating decays with  $K_S^0$  mesons occur in models with either heavy singlet Dirac neutrinos [1],  $R$ -parity violation in SUSY [2] or dimension-six effective fermionic operators that induce  $\tau - \mu$  mixing [3]. Experiments at the  $B$ -factories allow searches for such decays with a very high sensitivity. The best upper limits of  $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 9.1 \times 10^{-7}$  and  $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 9.5 \times 10^{-7}$  at the 90% confidence level were obtained in the CLEO experiment using  $13.9 \text{ fb}^{-1}$  of data [4].

In this paper, we report on a search for LFV  $\tau$  decays  $\tau^- \rightarrow \ell^- K_S^0$  ( $\ell = e$  or  $\mu$ ) [†] with a data sample of  $281 \text{ fb}^{-1}$  collected at the  $\Upsilon(4S)$  resonance and 60 MeV below it with the Belle detector at the KEKB  $e^+e^-$  asymmetric-energy collider [5].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect  $K_L^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [6].

Particle identification is very important in this measurement. Particle identification likelihood variables are based on the ratio of the energy deposited in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, the particle range in the KLM, the hit information from the ACC, the measured  $dE/dX$  in the CDC and the particle's time-of-flight from the TOF. For lepton identification, we use a likelihood ratio based on the electron probability  $\mathcal{P}(e)$  [7] and muon probability  $\mathcal{P}(\mu)$  [8] determined by the responses of the appropriate subdetectors.

For Monte Carlo (MC) studies, the following programs have been used to generate background events: KORALB/TAUOLA [9] for  $\tau^+\tau^-$ , QQ [10] for  $B\bar{B}$  and continuum, BHLUMI [11] for Bhabha events, KKMC [12] for  $e^+e^- \rightarrow \mu^+\mu^-$  and AAFH [13] for two-photon processes. Signal MC is generated by KORALB/TAUOLA. Signal  $\tau$  decays are two-body and assumed to have a uniform angular distribution in the  $\tau$  lepton's rest frame. The Belle detector response is simulated by a GEANT 3 [14] based program. All kinematic variables are calculated in the laboratory frame unless stated otherwise. In particular, variables calculated in the  $e^+e^-$  center-of-mass (CM) frame are indicated by the superscript “CM”.

## DATA ANALYSIS

We search for  $\tau^+\tau^-$  events in which one  $\tau$  (signal side) decays into  $\ell K_S^0$  where  $\ell$  is  $e$  or  $\mu$  and  $K_S^0$  decays into  $\pi^+\pi^-$ , while the other  $\tau$  (tag side) decays into one charged particle of opposite sign to the lepton with any number of additional photons and neutrinos. Thus, the experimental signature is:

$$\{\tau^- \rightarrow \ell^- (= e^- \text{ or } \mu^-) + K_S^0 (\rightarrow \pi^+\pi^-)\} + \{\tau^+ \rightarrow (\text{a track})^+ + (n_\gamma^{\text{TAG}} \geq 0) + X(\text{missing})\}.$$

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[†] Unless otherwise stated, charge conjugate decays are implied throughout this paper.

All charged tracks and photons are required to be reconstructed within the fiducial volume defined by  $-0.866 < \cos \theta < 0.956$ , where  $\theta$  is the polar angle with respect to the direction opposite to the  $e^+$  beam. Charged tracks should have momentum transverse to the  $e^+$  beam  $p_t > 0.1$  GeV/ $c$  and photons should have energies  $E_\gamma > 0.1$  GeV.

Signal events are isolated with following selections. We first demand that the four tracks have zero net charge. The magnitude of the thrust [15] is required to be larger than 0.9 to suppress the  $q\bar{q}$  continuum background. The event must have a 3-1 prong configuration relative to the plane perpendicular to the thrust axis. The  $K_S^0$  is reconstructed from two oppositely-charged pions that have an invariant mass within  $0.482 \text{ GeV}/c^2 < M_{\pi^+\pi^-} < 0.514 \text{ GeV}/c^2$ . The  $\pi^+\pi^-$  vertex is required to be displaced from the interaction point (IP) in the direction of the pion pair momentum [16]. In order to avoid fake  $K_S^0$  candidates from photon conversions (i.e.  $\gamma \rightarrow e^+e^-$ ), the invariant mass reconstructed by assigning the electron mass to the tracks, is required to be greater than  $0.2 \text{ GeV}/c^2$ . We apply the lepton identification requirements to each track except for the two tracks that are part of the  $K_S^0$  candidate on the signal side. The electron and muon identification criteria are  $\mathcal{P}(e) > 0.9$  with  $p > 0.3$  GeV/ $c$  and  $\mathcal{P}(\mu) > 0.9$  with  $p > 0.6$  GeV/ $c$ , respectively. After the event selection described above, most of the remaining background comes from  $\tau^+\tau^-$  and continuum events including a single  $K_S^0$  meson.

To ensure that the missing particles are neutrinos rather than photons or charged particles that are outside the detector acceptance, we impose additional requirements on the missing momentum vector,  $\vec{p}_{\text{miss}}$ , calculated by subtracting the vector sum of the momenta of all tracks and photons from the sum of the  $e^+$  and  $e^-$  beam momenta. We require that the magnitude of  $\vec{p}_{\text{miss}}$  be greater than  $0.4 \text{ GeV}/c$  and that it point into the fiducial volume of the detector:  $-0.866 < \cos \theta_{\text{miss}} < 0.956$ , as shown for the  $\tau^- \rightarrow \mu^- K_S^0$  mode in Fig. 1 (a) and (b). The total visible energy in the CM frame  $E_{\text{vis}}^{\text{CM}}$ , is defined as the sum of the energies of the  $K_S^0$  candidate, the lepton, the tag-side track (with pion mass assumed) and all photon candidates. We require it to satisfy  $5.29 \text{ GeV} < E_{\text{vis}}^{\text{CM}} < 10.0 \text{ GeV}$  (see Fig. 1 (c)). Since neutrinos are emitted only on the tag-side, the direction of  $\vec{p}_{\text{miss}}$  should lie within the tag-side of the event. The cosine of the opening angle between  $\vec{p}_{\text{miss}}$  and the tag-side track in the CM system,  $\cos \theta_{\text{tag-miss}}^{\text{CM}}$  is therefore required to be greater than 0 (see Fig. 1 (d)). To suppress the continuum background, the following requirements on the number of the photon candidates on the signal and tag side are imposed:  $n_\gamma^{\text{SIG}} \leq 1$  and  $n_\gamma^{\text{TAG}} \leq 2$ , respectively.

Finally, the correlation between the reconstructed momentum of the  $\ell K_S^0$  system,  $p_{\ell K_S}$ , and the cosine of the opening angle between the lepton and  $K_S^0$ ,  $\cos \theta_{\ell K_S}$  is employed to exclude background from generic  $\tau^+\tau^-$  and continuum:  $\cos \theta_{\ell K_S} < 0.14 \times \log(p_{\ell K_S} - 2.7) + 0.7$ , where  $p_{\ell K_S}$  is in GeV/ $c$  (see Fig. 2). While this condition retains 99% of the signal events, 99% of the generic  $\tau^+\tau^-$  and 84% of the  $uds$  continuum background are removed. The signal detection efficiencies for the  $\tau^- \rightarrow e^- K_S^0$  and  $\tau^- \rightarrow \mu^- K_S^0$  modes are 15.0% and 16.2% after all criteria applied, respectively.

## RESULTS

Signal candidates are examined in the two-dimensional space of the  $\ell^- K_S^0$  invariant mass,  $M_{\text{inv}}$ , and the difference of their energy from the beam energy in the CM system,  $\Delta E$ . A signal event should have  $M_{\text{inv}}$  close to the  $\tau$ -lepton mass and  $\Delta E$  close to 0. For both modes, the  $M_{\text{inv}}$  and  $\Delta E$  resolutions are parameterized from the MC distributions around the peak

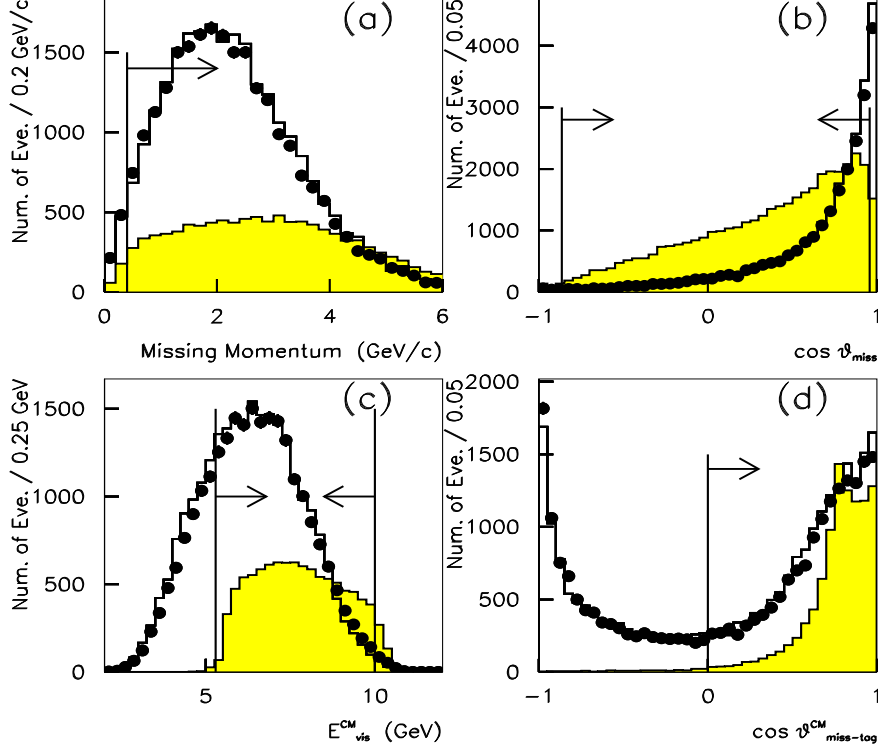


FIG. 1: Kinematical distributions used in the event selection after  $K_S^0$  mass and muon identification requirements: (a) the momentum of the missing particle; (b) the polar angle of the missing particle; (c) the total visible energy in the CM frame; (d) the opening angle between the missing particle and tag-side track in the CM frame. The signal MC distributions are indicated by the filled histograms, the total background including  $\tau^+\tau^-$  and  $q\bar{q}$  is shown by the open histogram, and closed circles are data. While the signal MC ( $\tau^- \rightarrow \mu^- K_S^0$ ) distribution is normalized arbitrarily, the data and background MC are normalized to the same luminosity. Selected regions are indicated by arrows from the marked cut boundaries.

with bifurcated Gaussian shapes to account for initial state radiation. These have widths  $\sigma_{M_{\text{inv}}}^{\text{high/low}} = 6.2/7.4 \text{ MeV}/c^2$  and  $\sigma_{\Delta E}^{\text{high/low}} = 20/26 \text{ MeV}$ , for the  $\tau^- \rightarrow e^- K_S^0$  mode and,  $\sigma_{M_{\text{inv}}}^{\text{high/low}} = 6.1/5.9 \text{ MeV}/c^2$  and  $\sigma_{\Delta E}^{\text{high/low}} = 19/23 \text{ MeV}$ , respectively for the  $\tau^- \rightarrow \mu^- K_S^0$  mode, where the “high/low” superscript indicates the higher/lower side of the peak.

We blind a region of  $\pm 5\sigma_{M_{\text{inv}}}$  around the  $\tau$  mass in  $M_{\text{inv}}$  and a region of  $-0.5 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$  so as not to bias our choice of selection criteria. Figure 3 shows scatter-plots for data and signal MC samples distributed over  $\pm 15\sigma$  in the  $M_{\text{inv}} - \Delta E$  plane. Most of the surviving background events in both modes come from  $D^\pm \rightarrow \pi^\pm K_S^0$  and  $D^\pm \rightarrow \ell^\pm \nu K_S^0$  decays. The remaining continuum backgrounds in the  $\tau^- \rightarrow \mu^- K_S^0$  mode are combinations of a true  $K_S^0$  meson and a fake lepton.

To optimize the sensitivity for the search, we use an elliptically shaped signal region, which has major and minor axes that correspond to  $\pm 5\sigma$  in the MC resolution for the  $M_{\text{inv}} - \Delta E$  plane. This region is shown in Fig. 3 (a) and (b). Signal efficiencies for this region after all requirements are 11.8% for  $\tau^- \rightarrow e^- K_S^0$  and 13.5% for  $\tau^- \rightarrow \mu^- K_S^0$ , respectively.

As there are few remaining MC background events in the signal ellipse, we estimate the



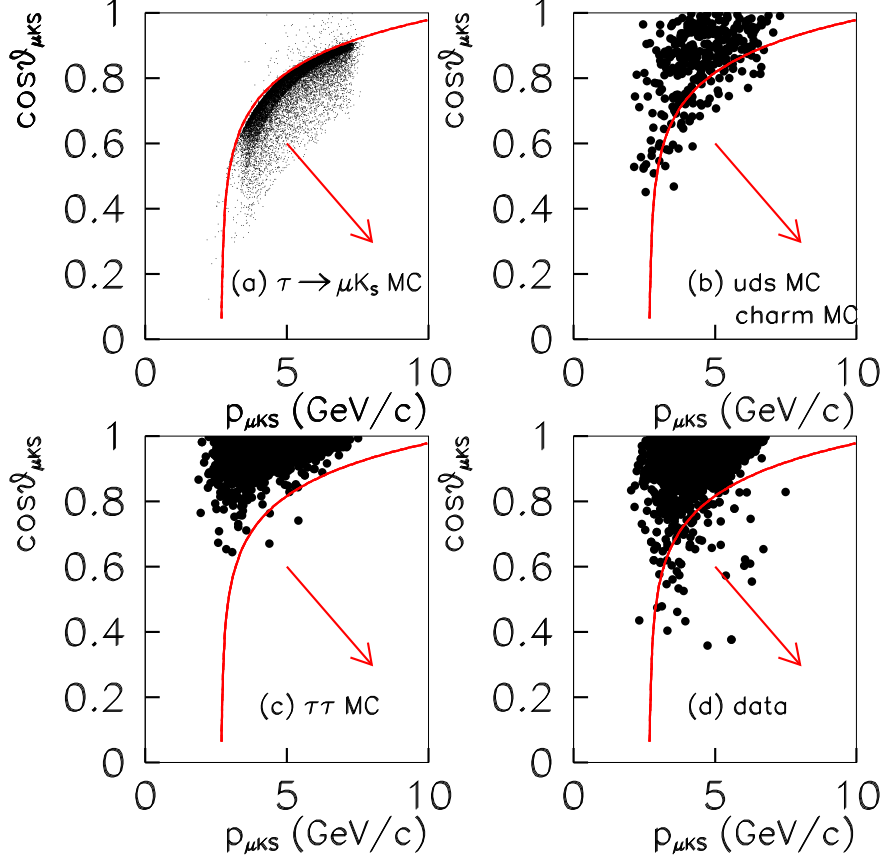


FIG. 2: Scatter-plots of (a) signal MC ( $\tau^- \rightarrow \mu^- K_S^0$ ), (b) continuum MC, (c) generic  $\tau^+\tau^-$  MC events and (d) data on the  $p_{\ell K_S}$  vs  $\cos \theta_{\ell K_S}$  plane. Selected regions are indicated by curves with arrows.

background contribution using the  $M_{\text{inv}}$  sideband regions. This is achieved by extrapolating to the signal region under the assumption that the background distribution is flat in  $M_{\text{inv}}$ . We find the expected background in the ellipse to be  $0.2 \pm 0.2$  events for each of the two modes. We open the blinded region and find no data events for the  $\tau^- \rightarrow e^- K_S^0$  and  $\tau^- \rightarrow \mu^- K_S^0$  modes (see Fig. 3 (a) and (b)). Since no statistically significant excess of data over the expected background in the signal region is observed, we apply a frequentist approach to calculate upper limits for the signal yields [17]. The resulting limits for the signal yields at 90% confidence level,  $s_{90}$ , are 2.23 events in both modes. The upper limits on the branching fraction before the inclusion of systematic uncertainties are then calculated as

$$\mathcal{B}(\tau \rightarrow \ell^- K_S^0) < \frac{s_{90}}{2\varepsilon N_{\tau\tau} \mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)} \quad (1)$$

where  $N_{\tau\tau} = 250 \times 10^6$  and  $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-) = 0.6895$  [18]. The resulting values are  $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.5 \times 10^{-8}$  and  $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.8 \times 10^{-8}$ .

The dominant systematic uncertainties on the detection sensitivity:  $2\varepsilon N_{\tau\tau} \mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$  come from  $K_S^0$  reconstruction and tracking efficiencies. These are 4.5% and 4.0%, respectively, for both modes. Other sources of the systematic uncertainties are: the trigger efficiency (0.5%), lepton identification (2.0%), MC statistics (0.3%), and luminosity (1.4%).

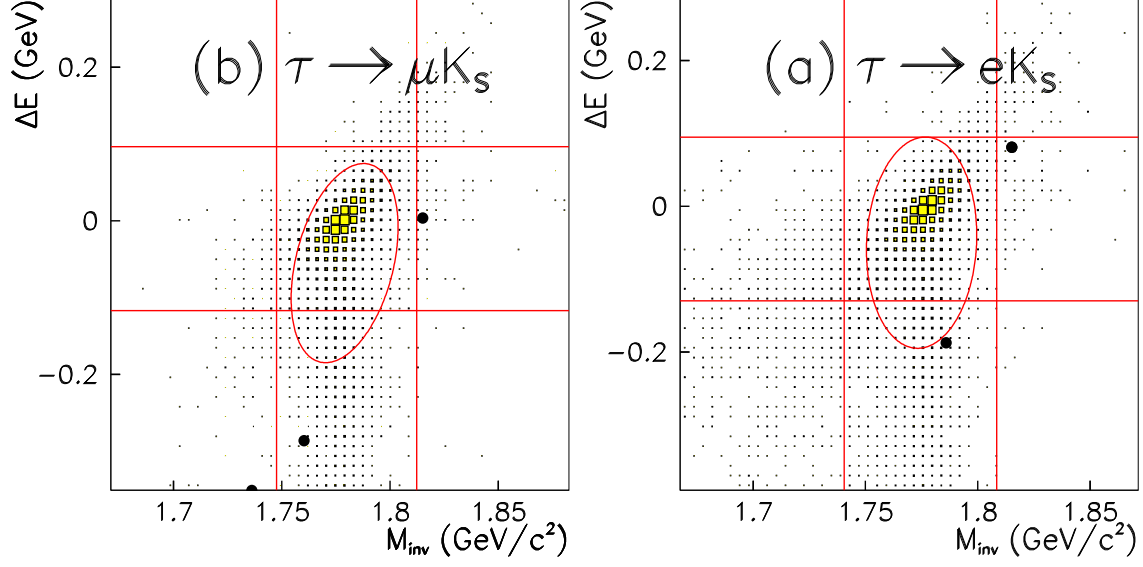


FIG. 3: Scatter-plots of data in the  $M_{\text{inv}} - \Delta E$  plane: (a) and (b) correspond to the  $\pm 15\sigma$  area for the  $\tau^- \rightarrow e^- K_S^0$  and  $\tau^- \rightarrow \mu^- K_S^0$  modes, respectively. The elliptical signal region shown by a solid curve in (a) and (b) is used for evaluating the signal yield. In (a) and (b), the vertical and horizontal lines denote  $\pm 5\sigma$ . Closed circles correspond to the data. The filled boxes show the MC signal distribution with arbitrary normalization.

Assuming no correlation between them, all these uncertainties are combined in quadrature to give a total of 6.5%.

Upper limits on the branching fractions at the 90% C.L. including these systematic uncertainties are calculated with the POLE program without conditioning [19]. The resulting upper limits on the branching fractions are

$$\begin{aligned}\mathcal{B}(\tau^- \rightarrow e^- K_S^0) &< 5.6 \times 10^{-8} \\ \mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) &< 4.9 \times 10^{-8}.\end{aligned}$$

## SUMMARY

In conclusion, we have searched for the lepton flavor violation decays  $\tau^- \rightarrow \ell^- K_S^0$  ( $\ell = e$  or  $\mu$ ) using data collected with the Belle detector at the KEKB  $e^+e^-$  asymmetric-energy collider. We found no signal in either mode. The following upper limits on the branching fractions were obtained:  $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.6 \times 10^{-8}$  and  $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.9 \times 10^{-8}$  at the 90% confidence level and including systematic uncertainties. These results improve the search sensitivity by factors of 16 and 19, respectively, compared to the previous limits obtained by CLEO experiment.

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